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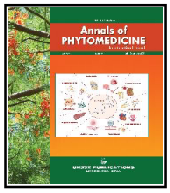

Review Article : Open Access

A comprehensive review on nutraceutical properties and pharmacological benefits for human healthcare in Jamun (*Syzygium cumini* (L.) Skeels)

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Abstract

Jamun (*Syzygium cumini* (L.) Skeels) is a fruit rich in bioactive compounds, boosting a health benefits that have long been recognized in traditional medicine systems. Firstly, *S. cumini* is packed with bioactive compounds such as anthocyanins, ellagic acid, and flavonoids, which contribute to its antioxidant, anti-inflammatory and antidiabetic properties. These compounds not only scavenge free radicals but also exhibit anticancer and antimicrobial activities, making it into a potent natural remedy for various ailments. Moreover, the pharmacological activities of *S. cumini* have been extensively studied. Research indicates its effectiveness in managing conditions like diabetes, cardiovascular diseases and gastrointestinal disorders. Fruit extracts have shown promising results in lowering blood glucose levels, reducing cholesterol and improving insulin sensitivity, thus offering a holistic approach to diabetes management. Additionally, its antihypertensive and cardioprotective effects make it a valuable asset in combating cardiovascular ailments. Furthermore, *S. cumini* demonstrates remarkable potential in the realm of neuroprotection and cognitive health. Studies suggest that its bioactive constituents possess neuroprotective properties, shielding against neurodegenerative disorders like Alzheimer's and parkinson's diseases. Additionally, Fruit extracts exhibit anti-inflammatory effects in the central nervous system, potentially alleviating symptoms associated with neurological conditions. Nano-based formulations originating from *S. cumini* extracts provide increased bioavailability, precise delivery, and extended release of active ingredients, thereby enhancing their therapeutic efficacy against diverse conditions such as diabetes, inflammation, cancer and microbial infections. These nano-enhanced *S. cumini* formulations demonstrate enhanced stability, solubility and absorption by cells, ensuring optimized therapeutic effects. This paper delves into the multifaceted properties of *S. cumini*, focusing on its neutraceutical and pharmacological potential.

1. Introduction

The *Syzygium cumini* (L.) Skeels fruit, scientifically known as *S. cumini* (Synonyms: *Myrtus cumini*, *Calyptranthes jambolana*, *Syzygium jambolanum*, *Eugenia jambolana*, *Eugenia cumini*), is part of the Myrtaceae family and is highly perishable, typically lasting only 1-2 days under regular conditions. It goes by various names such as “Brahaspati” in Sanskrit and commonly referred to as portuguese plum, java plum, malabar plum, black plum in English, Indian blackberry, *S. cumini* in Urdu, Jambu in Sanskrit, Jambul in Marathi, jambool and naval (Ramya *et al*., 2012). Originating from the Indian subcontinent and nearby regions in Southeast Asia, Southern China, East Africa and Eastern Australia. It is cultivated in several tropical areas including the West Indies, East and West Africa, as well as subtropical regions like Algeria and Israel (Oliveira *et al*., 2016). Global production estimates reach around 13.5 million tonnes, with China leading as the largest producer and India following closely behind, accounting for approximately 15.4% of the total production (Bukya and Madane, 2018).

Every component of the *S. cumini* tree holds medicinal significance. The commercial production of *S. cumini* seed powder in India by herbal manufacturers has proven highly beneficial for diabetes patients (Sarkar *et al*., 2015). Additionally, nanoparticles synthesized from *S. cumini* leaf and plant extracts have demonstrated effectiveness in various applications such as bioremediation and biocontrol (Raju *et al*., 2014). Research has shown that different parts of the *S. cumini* plant possess a myriad of medicinal properties including antioxidant, anti-inflammatory, neuropsycho pharmacological, antimicrobial, antibacterial, anti-HIV, antileishmanial, antifungal, nitric oxide scavenging, free radical scavenging, antidiarrheal, antifertility, gastroprotective, antiulcerogenic and radioprotective activities. Nowadays, in our society, peoples mostly depend on synthetic products to meet out their daily nutritional requirements. Though, there is abundant nutraceutical and medicinal benefits of *S. cumini*, its underutilization has resulted in limited exploration of its potential. So, this article explores the diverse characteristics of *S. cumini*, with a specific emphasis on its nutraceutical and pharmacological capacities. Many plant derived physiologically active ingredients have been studied for their potential in disease prevention and health

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enhancement (Atale *et al*., 2021; Jagetia, 2017; Zhang, *et al*., 2022; Mueller *et al*., 2015; Porika and Suchithra, 2022; Ramteke *et al*., 2015; Sahu *et al*., 2020; Xu *et al*., 2018; Yadav and Srivastava, 2014).

2. Nutritional composition

The nutritional composition of *S. cumini* varies depending on factors such as soil fertility, environmental conditions and harvesting methods (Ayyanar and Subash Babu, 2012). *S. cumini* seeds are a source of iron (1.40-42.00 µg/g), calcium (6.51-1358.60 µg/g), magnesium (0.10-1116.00 µg/g), phosphorus (720-6220 µg/g), potassium (130.50-6064.60 µg/g) and zinc (0.09-8.69 µg/g) (Ghosh *et al.*, 2017). Potassium regulating blood pressure and magnesium and calcium essential for cellular metabolism and bone health (Kshirsagar *et al*., 2019). *S. cumini* seeds also contain various vitamins, including water soluble ones like ascorbic acid (1.84-35.75 mg/100 g), niacin (0.09-0.11 mg/100 g), vitamin B_3 (0.09-0.13mg/100 g) and vitamin C (0.13-0.21 mg/100 g), as well as fat soluble vitamin retinol (3 IU/100 g) (Ghosh *et al*., 2017; Tak *et al*., 2022). Additionally, *S. cumini* tree leaves contain protein (6-9.1 g/100 g), fat (2.2-4.3 g/100 g), crude fiber (11.0-17.0 g/100 g), phosphorus (0.13-0.19 g/100 g), calcium (1.3-2.3 g/100 g) and essential oils contributing to their pleasant aroma (Ramteke *et al*., 2015). The nutritional composition and nutritional values of *S. cumini* are shown in Figures 1, 2, 3 and Table 1, respectively.

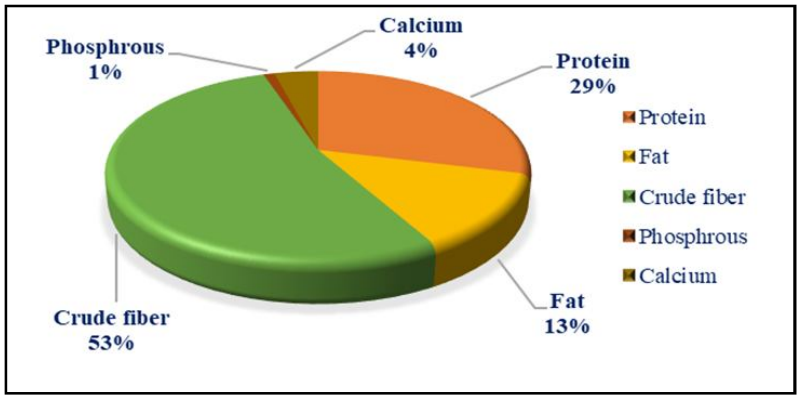

Figure 1: Nutraceutical composition of leaf of *S. cumini*.

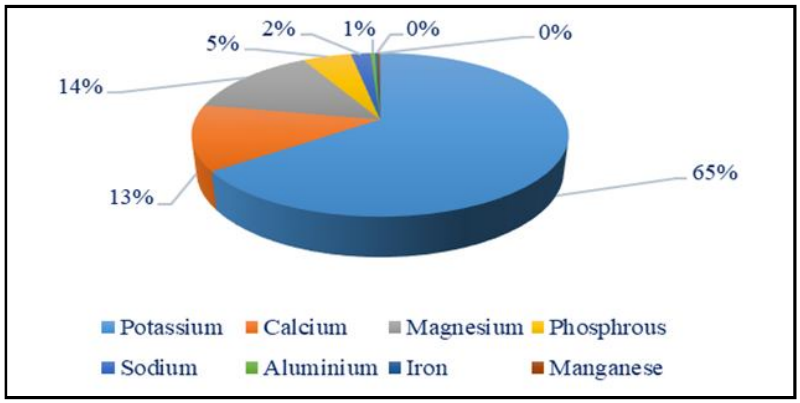

Figure 2: Nutraceutical composition of fruit pulp of *S. cumini*.

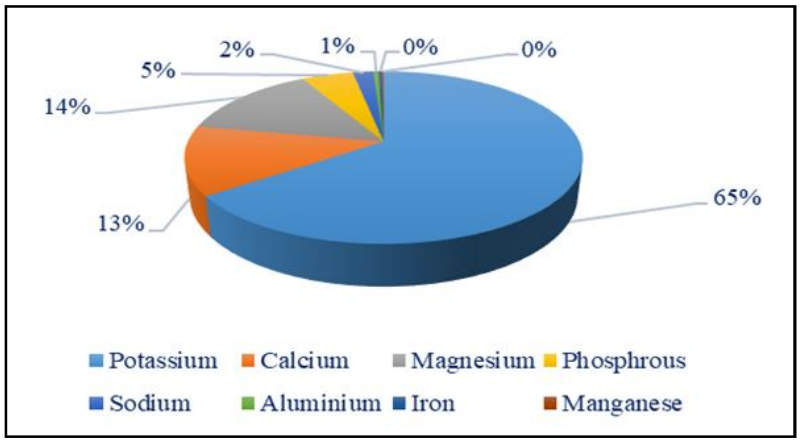

Figure 3: Nutraceutical composition of seeds of *S. cumini*.

Table 1: Plant parts with their nutritional values

Plant parts	Nutritional profile	Range of values (mg/100 g)	References
Fruit	Protein	0.70-0.13	Ghosh *et al.* (2017); Katiyar *et al.* (2016); Payel *et al.* (2018)
	Fat	0.15-0.30	
	Crude fibre	0.30-0.90	
	Calcium	0.08-0.15	
	Magnesium	0.035-0.056	
	Phosphorus	0.015-0.016	
	Iron	0.001-0.01	
	Sodium	0.026-0.037	
	Potassium	0.055-0.068	
	Copper	0.02-0.03	
	Thiamine	0.03-0.06	
	Riboflavin	0.09-0.01	
	Niacin	0.20-0.29	
	Ascorbic acid	5.70-18.00	
Seeds	Iron	1.40-42.00	Das *et al.* (2023); Eshwarappa *et al.* (2014); Katiyar *et al.* (2016)
	Calcium	6.51-13.60	
	Magnesium	0.10-16.00	
	Phosphorus	0.62-72	
	Potassium	0.13-0.60	
	Zinc	0.09-8.69	
	Ascorbic acid	1.84-35.75	
	Niacin	0.09-0.11	
	Vitamin B_3	0.09-0.13	
	Vitamin C	0.13-0.21	
Leaves	Protein	160-910	Katiyar *et al.* (2016); Parveen *et al.* (2020)
	Fat	220-430	
	Crude fiber	110-170	
	Phosphorus	130-190	
	Calcium	130-230	

3. Phytochemicals and their medicinal uses

S. cumini possesses high iron content, making it effective as a blood cleanser, aiding in the production of haemoglobin and serving as a beneficial dietary addition for women during menstruation. Diluted *S. cumini* juice is employed as gargle for relieving sore throats and applied topically as a remedy for scalp ringworm (Katiyar *et al.*, 2016). Powdered *S. cumini* seeds, when mixed with sugar, are orally administered 2-3 times daily for treating dysentery (Ramya *et al.*, 2012). The seeds also exhibit hypoglycemic properties, assisting in lowering blood glucose levels (Chaudhary and Mukhopadhyay, 2012). Extracts from *S. cumini* leaf gall contain various phytochemicals with antioxidant properties, beneficial for treating metabolic ailments such as diabetes mellitus, arthritis, cancer and liver disorders (Eshwarappa *et al.*, 2014).

Phytochemicals, derived from plants, possess the potential to offer health advantages when ingested, whether for medicinal purposes or as components of a well rounded diet. They play a crucial role in safeguarding against the development of diseases like cancer and heart disease (Tiwari *et al.*, 2015). Phytochemicals are considered a highly abundant source of new therapeutic agents (Kanwar *et al.*, 2018). Phytochemicals present in *S. cumini* are shown in Table 2.

3.1 Leaves

Many of the positive effects attributed to *S. cumini* leaves and stem from the presence of various phytochemicals within them, including gallic acid, tannins, mallic acid, flavonoids, essential oils, jambolin, ellagic acid, jambosine, antimellin and betulinic acid. Additionally, other phytochemicals like β-sitosterol, betulinic acid, mycaminose, crategolic (maslinic) acid, heptacosane, n-nonacosane, n-

hentriacontane, n-octacosanol, ntriacontanol, n-dotricontanol, quercetin, myricetin, myricitrin and the flavonol glycosides myricetin 3-O-(400-acetyl)-α L-rhamnopyranosides contribute to their beneficial properties (Singh *et al*., 2019). It is used to treat diabetes mellitus, cancer, liver disorder, arthritis and have antimicrobial and antioxidant property (Joshi *et al*., 2019).

3.2 Flowers

S. cumini flowers contain a range of phytochemicals that includes kaempferol, quercetin, myricetin, isoquercetin (quercetin-3-glucoside), myricetin-3-L-arabinoside, quercetin-3-D-galactoside, dihydromyricetin, oleanolic acid, erategolic acid (maslinic acid), galactoside, dihydromyricetin, acetyl oleanolic acid, eugenol triterpenoid A and eugenol triterpenoid B (Jagetia, 2017). It can be used as nematicide, colouring agent and possess antioxidant, antiviral and antiacne properties (Porika and Suchithra, 2022).

3.3 Seeds

The seeds contain a variety of phenolic compounds including phenolic acids, flavonoids, stilbenoids, coumarins, lignans and tannins. Predominantly, gallic and ellagic acids, gallotannins and ellagitannins are present. Phenolic acids such as protocatechuic acid, p-coumaric acid, caffeic acid, ferulic acid, chlorogenic acid, gallic acid, syringic acid, 5-hydroxyveratric acid and ellagic acid were identified (Eldin Elhawary *et al*., 2022; Gajera *et al*., 2017; Liu *et al*., 2018). Flavonoids like myricetin 3-O-glucoside, myricitrin, syringetin 3-O-glucoside, laricitrin, quercitrin, kaempferol, dihydromyricetin, catechin and epicatechin were found (Abdin *et al*., 2019; Eldin Elhawary *et al*., 2022). The presence of flavonoids in *S. cumini* was associated with its hypoglycemic, hypolipidemic and antiatherogenic effects. Specific compounds like schaftoside and apigenin 6,8-di-C-β-d-glucopyranoside were noted (Liu *et al*., 2018). Gallotannins like tannic acid and ellagitannins were observed to inhibit the canonical Wnt signaling pathway, indicating potential against colon carcinogenesis. Additionally, compounds such as 1,6-digalloyl glucose, 1,2,6-trigalloyl glucose, valoneic acid dilactone, corilagin, eugeniin, iso-oenothein C, rubuphenol, eschweilenol A and C, tergallic acid dilactone, decarboxy ellagic acid and 3,3',4'-tri-O- methyl ellagic acid were identified (Eldin Elhawary *et al*., 2022).

Jamunones A and spiralisone C, which are phloroglucinol derivatives, have been shown to inhibit the activity of protein tyrosine phosphatase 1B, suggesting their potential as agents against diabetes and obesity (Liu *et al*., 2017). Around 45 terpenes and terpenoids were identified, including α-pinene, β-pinene, limonene (monoterpenes), γ-terpineol (monoterpenoid), α-copaene, E-caryophyllene, α-humulene, α-selinene and D-germacrene (Scharf *et al*., 2016). Additionally, norsesquiterpenoids like jambolanes A and B were noted, along with sesquiterpenoids such as a mixture of jambolanins D and E, which exhibited antimicrobial activity against *Staphylococcus aureus* but not against *Escherichia coli* and *Candida albicans*. Moreover, compounds like actinidic acid, oleanolic acid, ursolic acid, corosolic acid, arjunolic acid, asiatic acid and betulinic acid were identified (Liu *et al*., 2017).

3.4 Fruits

The pulp of the *S. cumini* fruit contains compounds like anthocyanins, delphinidin, petunidin and malvidin-diglucosides, which give it its vibrant purple hue (Ramya *et al*., 2012). Additionally, it is rich in diglucosides of delphinidin, malvidin and cyaniding. It also contains volatile oils including α-pinene, β-pinene, β-myrcene, cis-ocimene, trans-ocimene, terpinolene, linalool, 4-terpineol, α-terpineol, cis-dihydrocarvone, caryophyllene, α-humelene, cis-β-farnesene, cis-α-farnesene, trans-α-farnesene, cis-nerolidol, geranyl butyrate, globulol, widdrol, torreyol, neocedranol and β-bisabolol (Aqil *et al*., 2014). The astringent taste of the fruit is attributed to gallic acid and tannins, while the occurrence of its purple color is due to cyanidin diglycosides (Anjali *et al*., 2017). Then, it also have the flavanol copounds such as diglucoside, myricetin pentoside, myricetin acetyl rhamnoside, dihydroquercetin diglucoside and myricetin (Jagetia, 2017).

3.5 Bark

The stem bark of *S. cumini* contains various compounds including betulinic acid, friedelin, epifriedelanol, β-sitosterol, eugenin and a fatty acid ester of epifriedelanol (Jagetia, 2017). Compounds such as quercetin, kaempferol, myricetin, gallic acid, ellagic acid, bergenins, flavonoids and tannins have been identified in the stem bark as well. Gallotannin, ellagitannin, myricetin and β-sitosterol are also reported in the bark (Porika and Suchithra, 2022). The presence of pentacyclic triterpenoid betulinic acid in *S. cumini* bark, demonstrating its potential role in selective cytotoxicity against specific tumors. Also, presence of β-sitosterol in the bark, which shares a similar chemical structure with cholesterol and is known for its cholesterol lowering and anti-inflammatory properties (Dagadkhair *et al*., 2017).

Table 2: Phytochemicals present in different plants and their extraction method

Plant parts	Phytochemicals	Extraction method	Uses	References
Leaves	Gallic acid, tannins, mallic acid, flavonoids, essential oils, jambolin, ellagic acid, jambosine, antimellin, betulinic acid, β-sitosterol, myca-minose, crategolic (maslinic) acid, heptacosane, n-nonacosane, n-hentriacontane, n-octacosanol, n-triacontanol, n-dotricontanol, quercetin, myricetin, myricitrin	Methanol and Dichloromethane	Antimicrobial, Antioxidant,	Joshi *et al*. (2019); Kumawat *et al*. (2018); Singh *et al*. (2019)
Flowers	Kaempferol, quercetin, myricetin, isoquercetin (quercetin-3-glucoside), myricetin-3-l-arabinoside, quercetin-3-D-galactoside, dihydromyricetin, oleanolic acid, erategolic acid (maslinic acid), galactoside, dihydromyricetin, acetyl oleanolic acid, eugenol-triterpenoid A and eugenol triterpenoid B	Methyl alcohol	Antioxidant, Antiviral, Antiacne properties, Nematicides, Colouring agent	Jagetia (2017); Porika and Suchithra (2022); Sahu *et al*. (2020)

Seeds	Protocatechuic acid, p-coumaric acid, caffeic acid, ferulic acid, chlorogenic acid, gallic acid, syringic acid, 5-hydroxyveratric acid and ellagic acid, myricetin 3-o-glucoside, myricitrin, syringetin 3-o-glucoside, laricitrin, quercitrin, kaempferol, dihydromyricetin, catechin, epicatechin, spiralisone C, jamunones A	Hydro alcoholic	Antidiabetes, Antiobesity, Antimicrobial, Anticancerous	Abdin *et al.* (2019); Eldin Elhawary *et al.* (2022); Hasan *et al.* (2022); Liu *et al.* (2018
Fruits	Delphinidin, malvidin, peonidin, cyanidin, α-pinene, β-pinene, β-myrcene, cis-ocimene, trans-ocimene, terpinolene, linalool, 4-terpineol, α-terpineol, cis-dihydrocarvone, caryophyllene, α-humelene, cis-β-farnesene, cis-α-farnesene, trans-α-farnesene, cis-nerolidol, geranyl butyrate, globulol, widdrol, torreyol, neocedranol	Acidified methanol, Lyophilized	Prevent DNA damage, Chemoprotective, Antiallergy, Anticancerous, Anti-inflammatory, Sedative	Anjali *et al.* (2017); Aqil *et al.* (2014); Charepalli *et al.* (2016); Jagetia (2017); Ramya *et al.* (2012)
Bark	Betulinic acid, friedelin, epi-friedelanol, β-sitosterol, eugenin, gallotannin, ellagitannin, myricetin and β-sitosterol	Hexane and Acetone	Anti-inflammatory, Antiobesity, Anticancerous	Jagetia (2017); Madani *et al.* (2021); Porika and Suchithra (2022)

4. Bioactive compounds

The term 'Bioactive' originates from the greekword "Bio," means "life," and latin word "Activus" means "Active". These are the additional, non-nutritional elements of food that are believed to have positive health effects, excluding essential nutrients (Nahler *et al.*, 2017). Nutrients in plants are typically not considered as part of the category "plant bioactive compounds." Bioactive compounds in plants are usually secondary metabolites that are not crucial for the plant's daily functions like growth but serve important roles in competition, defense, attraction and signaling (Guaadaoui *et al.*, 2014). The composition of bioactive compounds in *S. cumini* fruit varies depending on the plant's age and the fruit's maturity level. Anthocyanins may increase as the fruit matures, whereas ellagitannins, flavonols, gallic acid and ellagic acid may decrease, while fruit ripens (Lestario *et al.*, 2017). Plant parts and bioactive compounds of *S. cumini* are shown in Table 3, respectively.

4.1 Flavonoids

Flavonoids are plant derived secondary metabolites that act as reducing agents in chemical reactions and have the ability to bind with metals (Manju and Pushpa, 2020). The seed contains abundant flavonoids such as catechin, quercetin, kaempferol and epicatechin (Gajera *et al.*, 2017). Anthocyanins are the primary flavonoid present in the pulp of *S. cumini*, while rutin and myricetin are significant phytochemical constituents in *S. cumini* seeds (Khan *et al.*, 2019). Quercetin, with its anti-inflammatory, scavenging and thrombin inhibitory properties, may offer beneficial effects in preventing and treating COVID-19 (Atale *et al.*, 2021). Rutin, a flavonol, enhances blood capillary strength and exhibits antihypertensive, antioxidant and alpha glucosidase inhibitory properties (Suzuki and Morishita, 2016). The methanol extraction of flavonoids gives more effect than methylene chloride (Ulla *et al.*, 2017).

4.2 Phenolic compounds

Phenolic components in the *S. cumini* fruit extract (5103.03 mg GAE/100 g), which is low when compare to the *S. cumini* seed extract (4812.03 mg GAE/100 g) indicating superior antioxidant potential in combating free radical chain reactions and preventing oxidative damage. Major polyphenols found in *S. cumini* seeds, including ellagic (0.36 µg/g), gallic (0.87 µg/g), cinnamic (0.36 µg/g), ferulic (0.04 µg/g) and syringic acids (0.02 µg/g) have been identified to modulate and alleviate oxidative stress induced by tertiary buty-l-hydrogen peroxide (TBHP) in H_9C_2 cardiomyoblasts. This modulation extends to angiotensin converting enzyme (ACE), β-hydroxy β-methylglutaryl-CoA (HMG-CoA) reductase and low density lipoprotein (LDL) oxidation, potentially conferring a cardioprotective effect attributed to the phenolics in *S. cumini* (Raza *et al.*, 2015).

4.3 Anthocyanins

Anthocyanins such as delphinidin 3,5-diglucoside (256 mg/100 g), petunidin 3-glucoside (245 mg/100 g), malvidin 3,5-diglucoside (166 mg/100 g), petunidin 3,5-diglucoside (89 mg/100 g), peonidin 3,5-diglucoside (75 mg/100 g), delphinidin 3-glucoside (60 mg/100 g), delphinidin acetyl-diglucoside (53 mg/100 g), cyanidin 3-glucoside (39 mg/100 g), cyanidin 3,5-diglucoside (29 mg/100 g) and malvidin 3-glucoside (25 mg/100 g) are found in *S. cumini* fruit (Faria *et al.*, 2011). These anthocyanins present in the fruit pulp are not found in the seeds, possibly due to changes occurring during the fruit's ripening stage (Aqil *et al.*, 2012).

Malvidin has been found to specifically target and induce apoptosis in several cancer cell types, such as breast cancer cells (MCF-7), colon cancer cells (HT-29), and leukemia cells. This process is facilitated through mechanisms that include increasing oxidative stress, inhibiting cell proliferation, and activating specific pathways that lead to cell death. Malvidin aids in the growth and protection of healthy cells by acting as an antioxidant, reducing oxidative stress, and potentially enhancing cellular repair processes. These properties help maintain the health and integrity of noncancerous cells process called cAMP hydrolysis. Similarly, ellagic acid protects yeast cells from damage caused by gamma radiation by reducing DNA damage (Chhikara *et al.*, 2018).

4.4 Carotenoids

Approximately 700 varieties of natural carotenoids have been identified, yet only around 50 are capable of being absorbed, transported and stored by the human body. *S. cumini* fruit, contains β-carotenoid content of about 48 mg/100 g has been noted (Suradkar *et al.*, 2017). Primary carotenoids include lutein (0.39 µg/g), β-Carotene (0.23 µg/g), zeaxanthin (0.02 µg/g) and β-cryptoxanthin (0.003 µg/g), which have been linked to a decreased risk of specific ailments like cancer, cardiovascular disease and cataracts (Kim *et al.*, 2016).

4.5 Essential oils

The fruit and leaves of *S. cumini* contain diverse essential oils, with the leaves holding the majority, constituting 82% of the total essential oils. Notable components in the leaf essential oil include α-gurjeuene (38.35%), aromadendrene (6.62%), β-caryophyllene (6.96%) and guaiol (7.0%). In the pulp, essential oils such as terpeneol (8.9%), eucarvone (8.9%), myrtenol (5.8%), α-myrtenal (5.7 %), geranyl acetone (5.6%), α-cadinol (4.6%), pinocarvone (4.4%) and α-muurolol (0.13%) are present. β-sitosterol, structurally similar to cholesterol, exhibits pharmacological properties like anti-inflammatory, antimicrobial and hypolipidemic effects, aiding in lowering blood lipid levels (Chhikara *et al*., 2018).

Terpenes are natural chemicals found in all parts of the *S. cumini* plant, like its seeds, pulp, bark, leaves and flowers (Kalse *et al*., 2016). These are organic compounds made up of multiple smaller units called isoprenes. They do a lot of good things for us, like protecting our nerves, fighting tumors, reducing inflammation and killing germs. They are also good against things like fungus, viruses and parasites (Cho *et al*., 2017). Also make things smell nice, so they're used to add flavor to food and medicines (Singh *et al*., 2019). Another compound, called β-sitosterol, helps fight viruses like dengue by working as an antioxidant (Ríos and Máñez, 2018).

4.6 Tannins

Tannic acid, composing approximately 13.4% of *S. cumini* bark, has properties that protect the stomach and prevent ulcers (Bandiola *et al*., 2017). Tannins from *S. cumini*, present at a concentration of 20.0 g/kg, diminish stomach damage by decreasing the formation of harmful free radicals, thereby exhibiting antiulcerogenic effects. It has been documented that ellagic acid and urolithin A, metabolites derived from ellagitannins, which constitute about 20.5% of *S. cumini*'s phenolic content, reduce the development of colon cancer in human 293T cell lines by adjusting the activation of a Wnt pathway and notably, urolithin A is an active metabolite effective in regulating gut bacteria (Das *et al*., 2023).

4.7 Alkaloids

Alkaloids play a significant role in diabetes management, facilitating the conversion of starch into sugar in the bloodstream (Rajkumar *et al*., 2021). The existence of alkaloids in the acetone and chloroform extracts from *S. cumini* fruit seeds (Hasanuzzaman *et al*., 2016). Additionally, traditional records suggest minimal to no adverse effects from seed and bark extracts, although high tannin bark extracts could potentially cause mild gastrointestinal discomfort when consumed with food (Das *et al*., 2023)

Table 3: Bioactive compounds present in plant parts and their health benfits

Plant parts	Chemical compounds	Bioactive compounds	Health benefits	Reference
Seeds	Catechin, quercetin, kaempferol, epicatechinrutin	Flavonoids	Anti-inflammatory, Antihypertensive, Antioxidant	Gajera *et al*. (2017); Suzuki and Morishita (2016)
	Ellagic acid (0.36 µg/g), gallic acid (0.87 µg/g), ferulic acid (0.04 µg/g), cinnamic acid (0.36 µg/g), syringic acid (0.02 µg/g)	Phenolic compounds	Cardioprotective, Antioxidant	Raza *et al*. (2015)
Fruit pulp	Delphinidin 3,5-diglucoside (256 mg/100 g), petunidin 3-glucoside (245 mg/100 g), malvidin 3,5-diglucoside (166 mg/100 g), petunidin 3,5-diglucoside (89 mg/100 g), peonidin 3,5-diglucoside (75 mg/100 g), delphinidin 3-glucoside (60 mg/100 g), delphinidin acetyl-diglucoside (53 mg/100 g), cyanidin 3-glucoside (39 mg/100 g) and cyanidin 3,5-diglucoside (29 mg/100 g)	Anthocyanins	Antimicrobial	Chhikara *et al*. (2018)
	Lutein (0.39 µg per g), β-carotene (0.23 µg per g), zeaxanthin (0.02 µg per g), β-cryptoxanthin (0.003 µg per g)	Carotenoids	Anticancerous	Suradkar *et al*. (2017)
Leaves	α-gurjeuene (38.35%), aromadendrene (6.62%), β-caryophyllene (6.96%), guaiol (7.0%), terpeneol (8.9%), eucarvone (8.9%), myrtenol (5.8%).	Essential oils	Anti-inflammatory, Antimicrobial, Hypolipidemic	Chhikara *et al*. (2018)

5. Health benefits

5.1 Antioxidant activity

S. cumini seed extracts demonstrate multiple mechanisms of action, including the capture of various free radicals such as superoxide, hydroxyl, lipid peroxide, 2,2-diphenyl-1-picrylhydrazyl (DPPH) and nitric oxide. Additionally, they exhibit the ability to chelate transition metal catalysts like ferric ions (Kumawat *et al*., 2018). Phenolics found in these extracts, such as gallic acid, ellagic acid, ferulic acid, catechin and quercetin, contribute to their radical scavenging activity against DPPH, as evidenced by recent studies. Fruits are in rich source of calcium, potassium, dietary fibres and low phenolic compounds are responsible for the radical scavenging activity. Leaves contains phenolic compounds such as ferulic acid and catechin also contribute to antioxidant activity (Mahindrakar and Rathod, 2021).

5.2 Antimicrobial activity

S. cumini, is renowned not only for its delectable taste but also for its potential health benefits, including antimicrobial properties. Research has shown that various parts of the *S. cumini* tree, such as its leaves, bark and seeds, possess significant antimicrobial activity

against a wide range of pathogens including bacteria, fungi and viruses. The efficacy of leaf extracts against pathogens like *Escherichia coli*, *Staphylococcus aureus*, *Candida albicans* and Herpes simplex virus. These findings suggest that *S. cumini* could serve as a natural alternative to synthetic antimicrobial agents, potentially aiding in the development of novel antimicrobial drugs and nutraceuticals (Sharma *et al*., 2019).

5.3 Antibacterial activity

The stems and leaves are extracted by using methanol and acetones inhibit well against bacteria like *Roultella plantikol*, *Bacillus subtilis*, Salmonella, *Pseudomonas aeruginosa* and *E. coli*. Also, essential oils from *S. cumini* leaves inhibit bacteria such as *Bacillus sphaericus*, *Staphylococcus aureus*, *E. coli*, *Pseudomonas aeruginosa* and *Salmonella typhimurium* (Jagetia, 2017). *S. cumini* roots are well effective against bacteria like *S. aureus*, *S. epidermidis*, *E. coli*, *Streptococcus suis*, Salmonella and *Corynebacterium diphtheriae*. The root extract was especially better at killing gram positive bacteria compared to gram negative bacteria (Mueller *et al*., 2015).

5.4 Antifungal and antiviral activity

It was found that *S. cumini* bark and leaves can fight against a fungus called *Rhizoctonia solani*. The extracts from the bark were better at fighting the fungus compared to the extracts from the leaves (Porika and Suchithra, 2022). Bark and leaf extracts obtained by methanolic extraction subjected for inhibition of growth of *R. solan*. Researchers looked into how effective *S. cumini* leaf extracts are against two diseases that are becoming more common against buffalo pox and goat pox. They found that both the leaf and bark extracts of the *S. cumini* tree can effectively kill the avian influenza virus. They were able to completely prevent the H_5N_1 strain of the virus (Sahu *et al*., 2020).

5.5 Anti-inflammatory activity

S. cumini seed extract has anti-inflammatory effects in rats with high glucose levels affecting heart cells. The active ingredients in the extract protected the heart cells from stress caused by glucose, reducing harmful activities such as gelatinase production and movement of certain proteins within the cells. Docking studies also showed that the extract's phenolic compounds interact strongly with gelatinase B (Atale *et al*., 2021). Seed extract can inhibit DPP-4 and adenosine deaminase (ADA) in human blood cells. It is possible that the extract's active compounds affect how these cells communicate with each other through purinergic signaling (Bellé *et al*., 2013).

5.6 Antiallergic and antiarthritis activity

S. cumini root extracts were found to stop clonidine induced catalepsy in mice by stopping histamine release caused by mast cell degranulation, which leads to anaphylaxis. Also, giving mice with different *S. cumini* root extracts was shown to reduce milk induced eosinophilia. By aqueous extract of fruit contains flavonoids and hydrolysable tannins are confirmed by HPLC analysis effect against allergeic reactions. Methanolic extracts from dried seeds also have this effect (Balakrishna *et al*., 2016). The extracts from *S. cumini* leaf galls have antioxidants that could help treat arthritis (Eshwarappa *et al*., 2014).

5.7 Hepatoprotective activity

S. cumini fruit extract has been shown to protect liver cells from damage caused by bile duct ligation, hepatic fibrosis and immune cell infiltration by reducing oxidative stress and the expression of certain genes involved in inflammation. Additionally, *S. cumini* pulp extract can decrease the production of nitric oxide, which is involved in inflammation (Donepudi *et al*., 2012). It is believed that *S. cumini* may have the ability to eliminate harmful bacteria in the stomach. Rats exposed to carbon tetrachloride were treated with *S. cumini* seed extracts at a dosage of about 400 mg/kg, which effectively mitigated liver damage (Tak *et al*., 2022). Furthermore, administering methanolic *S. cumini* seed extract at a dose of 200 mg/kg body weight to diabetic rats demonstrated a hepatoprotective effect by improving protein levels and reducing abnormal liver enzymes (Nahid *et al*., 2017).

5.8 Cardioprotective activity

In ayurveda and unani medicine, it is customary to use *S. cumini* seeds to combat diabetes. Seeds have the potential to protect the heart because they contain a higher amount of phenolic compounds, which can lower intracellular oxidative stress, thus preventing the reduction of cellular antioxidants and enhancing cell viability. Studies suggest that these seeds may help alleviate glucose induced stress on H_9C_2 cardiac cell lines by hindering glycation. Seeds could serve as effective cardioprotective agents. Their richness in phenolic compounds may contribute to reducing intracellular oxidative stress, preserving cellular antioxidants and enhancing cell viability (Atale *et al*., 2013; Devkar *et al*., 2012).

5.9 Antidiabetic activity

The distinctive blend of phenolics and glycosides, including ellagic acid and jamboline, interrupts the enzymatic breakdown of starch into sugar. This action helps prevent diabetic complications such as neuropathy and cataracts, indicating the antidiabetic potential of the seed (Kumar, Hasan, *et al*., 2022). Mostly phenolic compounds and "mycaminose" is mainly responsible for antidiabetics. Seeds have more antidiabetics due to the kernels in the seed. Jamboline a and b extracted from seeds by using ethanolic extraction method act against diabetics. The compounds ellagic acid and ellagitannins contribute to reduce the glucose level in the blood (Sahu *et al*., 2020).

5.10 Hypoglycaemic activity

The hypoglycemic activity of *S. cumini* has gained significant attention due to its potential therapeutic implications in managing diabetes mellitus. *S. cumini*, traditionally used in various medicinal systems, contains bioactive compounds such as jamboline, ellagic acid and anthocyanins, which have been implicated in its antidiabetic properties. Studies have demonstrated that *S. cumini* extracts or its bioactive constituents can enhance insulin sensitivity, promote glucose uptake by cells, inhibit carbohydrate digesting enzymes and protect pancreatic β-cells. Notably, animal studies and some clinical trials have provided evidence supporting the hypoglycemic efficacy of *S. cumini*. However, further rigorous clinical trials are warranted to establish its efficacy and safety in human subjects. These findings underscore the potential of *S. cumini* as a natural therapeutic agent for diabetes (Kumari *et al*., 2023; Xu *et al*., 2018).

5.11 Antihyperlipidemic activity

The *S. cumini* seeds had a positive effect on reducing lipid levels in humans. Patients diagnosed with prediabetes who were given *S. cumini* seed capsules (4.5 g/day) saw significant improvements in total cholesterol and LDL-cholesterol levels (Parveen *et al*., 2020).

Supplementing rats' diets with *S. cumini* seed powder reduced white adipose tissue weights and lowered plasma lipid levels, including total cholesterol, triglycerides, LDL and HDL cholesterol concentrations, after 56 days on a high carbohydrate and high fat diet (Ulla *et al*., 2017).

5.12 Anticancerous activity

Fruit extract can cause cell death in colon cancer cells in a way that depends on how concentrated the extract is. They also discovered that a methanol extract of *S. cumini* fruit can increase cell death and slow down cell growth in lung cancer cells in a way that depends on its concentration, with an IC_{50} of 35.2 µg/ml (Charepalli *et al*., 2016). The pulp extract of *S. cumini* was found to effect againt breast cancer cells by inhibiting or killing of cancer causing cells by exhibiting cytotoxicity effect. Extract from pulp also induce cytotoxicity activity against colon cancer cells. The seed extract shows inhibitory action on lung cancer cells on concentration dependent manner (Jagetia, 2017).

5.13 Neuroprotective and gastroprotective activity

The *S. cumini* seed extract's phenolic compound includes inhibitors of dipeptidyl peptidase-4 (DPP-4), which are beneficial in treating alzheimer's disease. These compounds from *S. cumini* seeds have a protective effect on the brain against Alzheimer's disease (Kosaraju *et al*., 2014). Alzheimer's disease is a progressive neurodegenerative disorder marked by reduced levels of the neurotransmitter acetylcholine (ACh) in the brain. It is a type of dementia that worsens over time, leading to irreversible damage to mental functions and memory, and resulting in changes to personality and behavior (Bhattacharjee *et al*., 2020). Tannins sourced from the stem bark of *S. cumini* shield against gastric ulcers by diminishing damage to the stomach lining, decreasing free radicals and lowering ulcer formation on the stomach's mucous membrane. The ethanol extract derived from *S. cumini* seeds has been documented to alleviate peptic ulcers induced (Atale *et al*., 2013).

5.14 Radioprotective activity

S. cumini offers protection against radiation-induced mortality, illness, as well as intestinal and DNA harm by diminishing radiation triggered free radicals while enhancing a range of antioxidants. The radioprotective properties have gained attention due to its ability to mitigate radiation induced mortality, illness and damage to the intestines and DNA. Studies have shown that *S. cumini* achieves this by reducing the levels of radiation induced free radicals and bolstering various antioxidant defenses. Extracts from *S. cumini* leaves have been found to inhibit the formation of micronuclei induced by radiation exposure. These findings suggest that *S. cumini* possesses significant potential as a radioprotective agent (Shukla *et al*., 2023). Radioprotective activity of *S. cumini* fruit extract against radiation-induced sickness, mortality and intestinal mucosal damage in mice (Jagetia, 2017).

5.15 Antiacne activity

Research on the antiacne activity of *S cumini* has revealed promising results, attributed to its rich composition of bioactive compounds such as polyphenols, flavonoids and tannins. These components exhibit potent anti-inflammatory, antimicrobial, and antioxidant properties, which are crucial in managing acne vulgaris. Leaves have the ability to reduce inflammation, inhibit the growth of acne causing bacteria and scavenge free radicals, thereby preventing oxidative stress induced skin damage and promoting clearer skin. These findings underscore the potential of *S. cumini* as a natural remedy for acne management in skincare formulations (Sharma *et al*., 2019; Singh *et al*., 2019).

5.16 Antimalarial activity

More studies have unveiled its efficacy against a spectrum of pathogens, including bacteria, fungi and viruses. The bioactive compounds present in *S. cumini*, such as polyphenols, flavonoids and alkaloids, exert antimicrobial effects by disrupting microbial cell membranes, inhibiting vital enzymes and interfering with microbial adhesion and biofilm formation. *S. cumini* leaf extracts exhibit promising activity against notorious pathogens like *Staphylococcus aureus, E. coli, Candida albicans* and herpes simplex virus. Moreover, the antimicrobial potential of *S. cumini* extends to multidrug resistant strains, making it a compelling candidate for combating emerging infectious threats (Das *et al*., 2023; Singh *et al*., 2019).

5.17 Antileishmanial activity

Leishmaniasis, caused by protozoan parasites of the Leishmania genus, remains a significant health concern globally, particularly in tropical and subtropical regions. Studies have explored the potential of *S. cumini* extracts against Leishmania parasites, revealing promising results. The antileishmanial efficacy of *S. cumini* leaf extracts, attributing this activity to the presence of bioactive compounds such as polyphenols and flavonoids. Additionally, A recent study by Kumar (2020), further substantiated these findings, demonstrating the inhibitory effects of *S. cumini* extracts on Leishmania growth (Patra *et al*., 2020; Singh *et al*., 2019).

5.18 Antiulcerogenic activity

The gastroprotective effects of *S. cumini* seed extract against experimentally induced gastric ulcers in animal models. The study attributed this activity to the presence of bioactive compounds like tannins, flavonoids and polyphenols, which exerted antioxidant and cytoprotective effects on gastric mucosa. The antiulcerogenic potential of fruit extract, showing significant reduction in ulcer index and increase in gastric mucosal defense factors in rats. These findings suggest that *S. cumini* extracts possess gastroprotective properties and could serve as a natural remedy for gastric ulcers (Payel *et al*., 2018; Yadav *et al*., 2020).

6. Nanotechnological application

The seed extract of *S. cumini* can be used to create nano-particles by reducing them. They also discovered that the leaf extract can serve as both a capping agent and a reducing agent in making silver nano-particles (Prasad *et al*., 2012). Compared to traditional methods, using *S. cumini* for green nanoparticle production is simpler, more sustainable, safer, cheaper and more energy efficient. Additionally, these synthesized metal nanoparticles could be effective in adsorbing aflatoxin B1, a toxin found in human and animal food. A recent study in 2020, suggested that iron, copper and silver nano-particles can be formed from the extract of *S. cumini* leaves (Asghar *et al*., 2020). Nanoformulations derived from *S. cumini* extracts offer enhanced bioavailability, targeted delivery, and prolonged release of bioactive compounds, augmenting their therapeutic potential against various ailments including diabetes, inflammation, cancer, and microbial infections. These nanoenabled *S. cumini* formulations exhibit

improved stability, solubility and cellular uptake, ensuring optimized therapeutic outcomes. By harnessing nano-technology, *S. cumini* emerges as a potent source of bioactive compounds with significant implications for pharmaceutical and nutraceutical applications (Thomas *et al*., 2023). Nanoparticle coated materials are increasingly being embraced in dentistry due to the proven advantages of certain materials. Specifically, silver nanoparticles are being integrated into various dental products for their antimicrobial properties (Sreenivasagan *et al*., 2020). Food supplements and dietary formulations are developed with nutraceuticals to enhance health and manage or treat diseases (Subramoniam, 2014).

7. Future prospects

While *S. cumini* offers significant nutritional and medicinal benefits, commercial farming is still limited, particularly in arid and semiarid regions. The fruit is rich in bioactive compounds with potential pharmacological applications, yet there is a need for more research on the saponins and lignans in its seeds and the bioavailability of its compounds. To maximize its potential, attention should be given to developing value added products and exploring its use in functional foods and disease prevention. Future research should focus on identifying and understanding specific bioactive compounds, validating their health benefits through clinical studies, and optimizing cultivation and processing methods. Collaboration among scientists, agriculturists, and the pharmaceutical industry, alongside sustainable sourcing practices, will be essential for developing effective and consistent formulations and ensuring the long-term viability of *S. cumini* as a medicinal plant.

8. Conclusion

The *S. cumini* fruit, known for its appealing color, tangy flavor and significant mineral and vitamin content, is seasonal, perishable and often overlooked. *S. cumini* seeds are seen as a cost effective source of a natural antidiabetic substance, with increasing recognition of their antioxidant, anti-inflammatory and antimicrobial properties. With a high concentration of bioactive compounds like polyphenols, flavonoids and anthocyanins, *S. cumini* offers potent antioxidant, anti-inflammatory and antidiabetic effects. These qualities of *S. cumini* as a valuable natural remedy for various health conditions, including diabetes, cardiovascular diseases and disorders related to oxidative stress. Incorporating *S. cumini* into diets and healthcare practices shows promise for improving health outcomes and overall wellbeing. Raising awareness of *S. cumini*'s health benefits could contribute to building a healthier society.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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